View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by National Tsing Hua University Institutional Repository

Microwave-frequency-comb generation utilizing a semiconductor laser subject to optical pulse injection from an optoelectronic feedback laser

Yu-Shan Juan and Fan-Yi Lin*

Institute of Photonics Technologies, Department of Electrical Engineering, National Tsing Hua University, Hsinchu 300, Taiwan

Corresponding author: fylin@ee.nthu.edu.tw

Received November 4, 2008; revised April 23, 2009; accepted April 24, 2009; posted April 29, 2009 (Doc. ID 103551); published May 21, 2009

Microwave frequency combs are generated by optically injecting a semiconductor laser (slave) with repetitive pulses from an optoelectronic feedback laser (master). By varying the delay time, regular pulsing states with different pulsing frequencies are generated in the master laser. The pulsing output is then optically injected into the slave laser to produce desired microwave frequency combs. Microwave frequency combs with broad bandwidths and low nonharmonic spurious noise are demonstrated experimentally. To analyze their stabilities and spectral purities, single-sideband phase noise of each microwave frequency comb line is measured. Noise suppression of the microwave frequency comb relative to the injected regular pulsing state is also investigated. © 2009 Optical Society of America

OCIS codes: 140.5960, 350.4010, 140.3520, 140.2020.

Nonlinear dynamics of semiconductor lasers have been studied extensively in the past decade. Under different perturbations, such as optical injection [1], optic feedback [2], and optoelectronic feedback [3], various dynamical states including periodic oscillations, chaotic oscillation, harmonic frequency locking, periodic pulsations, quasiperiodic pulsations, and chaotic pulsations have been observed. To put them to practical use, applications that utilize the nonlinear characteristics of semiconductor lasers have been proposed and demonstrated [4,5], including optical chaotic communications, radio-over-fiber transmission, all-optical frequency conversion, and laser chaos-based lidar, radar, and sensors. Recently, microwave frequency combs generated with the harmonic frequency-locked states of a negative optoelectronic feedback (NOEF) laser have been studied [6]. However, severe nonharmonic spurious noise from the residual of the delay frequency and large amplitude variation limit the use of the microwave frequency comb generated. Moreover, the bandwidth of the microwave frequency comb generated is inevitably limited by the electronic bandwidth of the feedback loop to only a few gigahertz.

Recently, an optical frequency comb produced by the interaction between a cw pump laser and a monolithic ultra-high-Q microresonator via the Kerr nonlinearity has been successfully demonstrated [7]. Owing to its fixed physical structure of the resonant cavity, the line spacing is fixed and allows very limited tuning. Although optical frequency combs with large bandwidths and wide frequency spacings can also be generated by optical techniques such as mode-locking a laser [8] or modulating cw light with external modulators [9–11], spectral dispersion controls are necessary to faithfully convert the optical frequency combs into microwave frequency combs with a flat amplitude variation among comb lines, not to mention the fact that demanding stabilization for the mode-locked laser and expensive high-frequency synthesizers and modulators for the external modulation are needed for these techniques to generate optical frequency comb with gigahertz line spacing.

Therefore, in this Letter, microwave frequency comb generation using a semiconductor laser subject to optical pulse injection from an optoelectronic feedback laser is proposed and studied. By optically injecting a regular pulsing (RP) output from a master-laser (ML) subject to optoelectronic feedback into a slave laser (SL), microwave frequency combs with low nonharmonic spurious noise and wide bandwidths are obtained experimentally. To analyze their spectral purities and stabilities, single-sideband phase noise and drift for each comb line are measured. Since the only active optical devices used are two commercially available telecom diode lasers, the proposed scheme possesses the advantages of low cost, compact, less system complexity, and more flexibility in frequency tuning.

Figure 1 shows the schematic setup of the proposed laser-based microwave-frequency-comb-generation system. Two 1.3 μm single-mode distributed feedback semiconductor lasers are used as the ML and SL lasers. When biased at 30 mA, both lasers have relaxation resonance frequencies of about 7 GHz deduced from their noise spectra. The output light of the ML is divided into two parts, where one is used for the feedback and the other is used for injecting the slave laser. The photodetector PD1 (Albis PDCS65T) and the amplifier A1 (JCA JCA003-201) used in the feedback loop have bandwidths of 10 GHz and 3 GHz, respectively. By varying the delay time and the feedback strength with the movable mirror and the variable attenuator, respectively, RP states with different pulsing frequencies can be obtained [4]. In the experiment, the detuning frequency and the normalized injection strength from the ML to the

0146-9592/09/111636-3/$15.00 © 2009 Optical Society of America

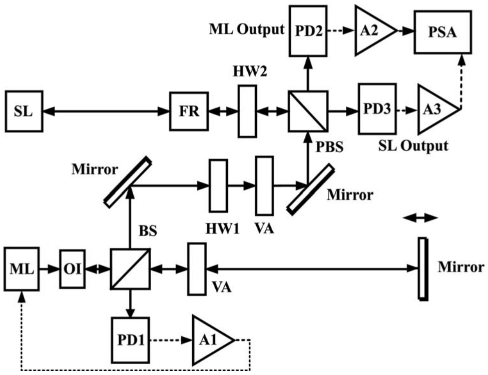

Fig. 1. Schematic setup of the proposed microwave-frequency-comb-generation system. The slave laser (SL) is optically injected by the regular pulsing state from a master laser (ML) subject to optoelectronic feedback. PD, photodetector; OI, optical isolator; BS, beam splitter; PBS, polarizing beam splitter; HW, half-wave plate; VA, variable attenuator; FR, Faraday rotator; A, amplifier; and PSA, power spectrum analyzer. Solid and dashed lines indicate optical and electrical paths, respectively.

SL are set at about 9.1 GHz and 0.31, respectively. The electrical power spectra are recorded using a power spectrum analyzer (Agilent E4407B) with a bandwidth of 26.5 GHz, where the photodetectors PD2 and PD3 (DSC30S) and the amplifiers A2 and A3 (MITEQ AFS6-00102000-30-10P-6) used to measure the respective ML and SL outputs have 3 dB bandwidths of 20 GHz.

Figures 2(a) and 2(b) show the power spectra of the ML and SL output, respectively, where the RP state of the ML has a pulsing frequency of 1.2 GHz. Although this RP state with frequency spacing of 1.2 GHz can also be used as a microwave frequency comb, only the first harmonic has a larger amplitude, while the amplitudes of the high-order harmonics are suppressed by the electronic bandwidth. Although it seems that electronic components with larger bandwidths could be adopted to overcome the bandwidth limitation effect of the RP state, in reality, since the pulsing frequency of the RP state will shift to a higher frequency as the electronic bandwidth increases [3], high-order harmonics will still inevitably fall beyond the already-increased bandwidth owing to the increasing of the line spacing. Hence, to generate a frequency comb with better amplitude flatness among comb lines, the RP state is further injected into a SL optically.

Figure 2(b) shows the power spectrum of the SL that is optically injected by the RP state from the ML. As can be seen, through optical injection, the energy in different harmonics are being redistributed more evenly through frequency beating and mixing, and the overall bandwidth extends to a higher frequency as well. Within a ±3 dB amplitude variation, the microwave frequency comb generated as shown has a 14 GHz bandwidth with 1.2 GHz line spacing. Compared with the harmonic frequency-locked states that show large nonharmonic spurious noise [6], the nonharmonic spurious noise in the microwave frequency comb generated is significantly lower. By simply varying the delay time to change the seeded RP state, frequency combs with different comb spacings or energy distributions can also be obtained. With our setup, the pulsing frequency of the RP states can be tuned in a range between 990 MHz to 2.6 GHz.

Figures 3(a) and 3(b) show the output spectra of the ML and SL where the RP state has a pulsing frequency of 990 MHz. Within a ±5 dB amplitude variation, the microwave frequency comb generated as shown has a 20 GHz bandwidth with 20 comb lines. The harmonics beyond 20 GHz are limited by the 3 dB bandwidth of the amplifiers (A2 and A3) and PDs (PD2 and PD3) used in the experiment. Note that through optical injection, redistribution of energy among each comb line together with the bandwidth enhancement effect [12,13] makes the generated microwave frequency combs have much broader bandwidths than the injected RP states. While stronger injection can further enhance the bandwidth, careful balancing between the frequency detuning and the injection strength is necessary for the SL to be locked and generate microwave frequency combs with flat spectra. Compared with the commercially available circuit-based comb generators that typically have ±20 dB in 20 GHz range [14], the microwave frequency comb generated utilizing nonlinear laser dynamics has a significantly smaller amplitude variation among the comb lines in the frequency range interested.

To analyze the spectral purity, single-sideband (SSB) phase noise of the microwave frequency comb is measured with the power spectral analyzer. Figure 4(a) shows the power spectra of the first harmonics of the output from the ML (middle curves) and the SL (lower curves) shown in Fig. 3 relative to the noise floor (horizontal line). As can be seen, both curves

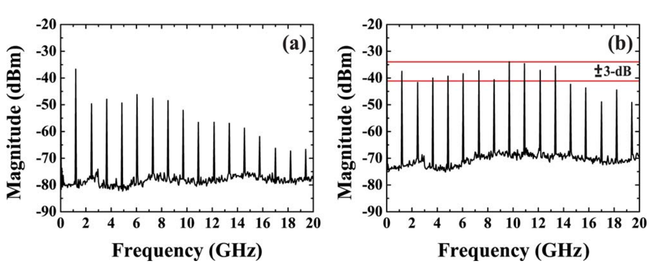

Fig. 2. (Color online) Power spectra of the (a) ML and (b) SL output for an injected regular pulsing state with 1.2 GHz pulsing frequency. Within a ±3 dB amplitude variation, the microwave frequency comb generated in (b) has a 14 GHz bandwidth.

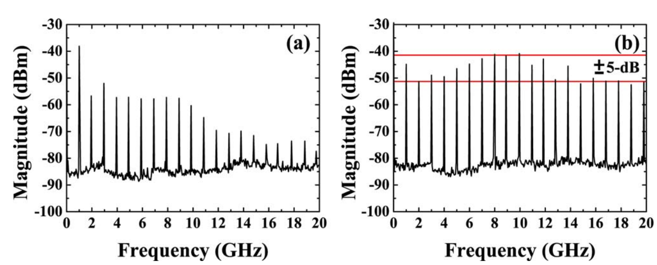

Fig. 3. (Color online) Power spectra of the (a) ML and (b) SL output for an injected regular pulsing state with 990 MHz pulsing frequency. Within a ±5 dB amplitude variation, the microwave frequency comb generated in (b) has a 20 GHz bandwidth.

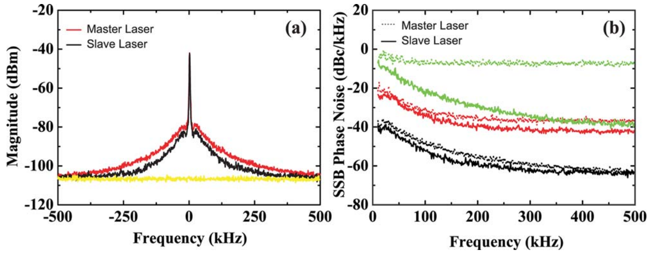

Fig. 4. (Color online) (a) Power spectra of the first harmonics of the output from the ML and SL relative to the noise level (horizontal line). (b) Single-sideband phase noise of the ML (dotted curves) and the SL (solid curves) for the first (lower curve), fourth (middle curves), and 11th (upper curves) harmonics at offset frequencies between 10 and 500 kHz. The resolution bandwidth is 1 kHz.

have a 3 dB linewidth less than 1 kHz, which is the resolution bandwidth of the spectrum analyzer. For the first harmonic of the microwave frequency comb generated, an SSB phase noise of −60 dBc/kHz (−90 dBc/Hz estimated) at an offset frequency of 200 kHz is measured. Moreover, by holding the spectrum at its maximum for 5 min, the drift of the peaks from the ML and SL lasers are measured to be within ranges less than 10.5 kHz and 7.4 kHz, respectively, mainly determined by the stability of the ML and the environmental fluctuations. The spectral purity and stability demonstrated is considered better than the microwave frequency comb generated from the harmonic frequency-locked states of the NOEF laser [6] and comparable with the optical frequency comb generated with the optoelectronic oscillator using a phase modulator [15].

Whereas the SSB phase noise in both the ML and the SL output increase as the order of harmonics increases as expected, noise suppression through optical injection [12,13,16] is observed in all of the comb lines that we have measured. Figure 4(b) shows the SSB phase noise of the ML (dotted curves) and the SL (solid curves) of the first, fourth, and 11th harmonics at offset frequencies between 10 kHz and 500 kHz. As can be seen, the SSB phase noise of the frequency components of the generated microwave frequency comb are significantly suppressed compared with the seeded RP state. For the 11th harmonic, an SSB phase-noise suppression of more than 30 dB relative to the SL output is achieved.

In conclusion, we study microwave-frequency-comb generation utilizing a semiconductor laser subject to optical pulse injection from an optoelectronic feedback laser. By optically injecting the slave laser with a regular pulsing output from the master laser subject to optoelectronic feedback, a 14 GHz microwave frequency comb with a flatness within ±3 dB (20 GHz within a flatness of ±5 dB) is demonstrated experimentally. Compared with the microwave frequency comb generated by the negative optoelectronic feedback semiconductor laser making use of the harmonic frequency-locked states, the frequency combs demonstrated have much lower nonharmonic spurious noise and wider bandwidths. An SSB phase noise of −60 dBc/kHz (−90 dBc/Hz estimated) is measured at an offset frequency of 200 kHz for the first harmonic, and a noise suppression of more than 30 dB relative to the SL output in the 11th harmonic is achieved.

This work is supported by the National Science Council of Taiwan (NSCT) under contract NSC 97-2112-M-007-017-MY3.

References

1. T. B. Simpson, J. M. Liu, K. F. Huang, and K. Tai, Quantum Semiclassic. Opt. **9**, 765 (1997).
2. A. Hohl and A. Gavrielides, Phys. Rev. Lett. **82**, 1148 (1999).
3. S. Tang and J. M. Liu, IEEE J. Quantum Electron. **37**, 329 (2001).
4. F. Y. Lin and J. M. Liu, IEEE J. Quantum Electron. **40**, 682 (2004).
5. S. C. Chan, R. Diaz, and J. M. Liu, Opt. Quantum Electron. **40**, 83 (2008).
6. S. C. Chan, G. Q. Xia, and J. M. Liu, Opt. Lett. **32**, 1917 (2007).
7. P. Del'Haye, A. Schiliesser, O. Arcizet, T. Wilken, R. Holzwarth, and T. J. Kippenberg, Nature **450**, 1214 (2007).
8. H. Y. Ryu, H. S. Moon, and H. S. Suh, Opt. Express **15**, 11396 (2007).
9. C. B. Huang, S. G. Park, D. E. Leaird, and A. M. Weiner, Opt. Express **16**, 2520 (2008).
10. S. Bennett, B. Cai, E. Burr, O. Gough, and A. J. Seeds, IEEE Photon. Technol. Lett. **11**, 551 (1999).
11. S. Ozharar, F. Quinlan, I. Ozdur, S. Gee, and P. J. Delfyett, IEEE Photon. Technol. Lett. **20**, 36 (2008).
12. J. M. Liu, H. F. Chen, X. J. Meng, and T. B. Simpson, IEEE Photon. Technol. Lett. **9**, 1325 (1997).
13. T. B. Simpson and J. M. Liu, IEEE Photon. Technol. Lett. **7**, 709 (1995).
14. For example, Picosecond Pulse Labs model 7112 comb generator.
15. T. Sakamoto, T. Kawanihsi, and M. Izutsu, Opt. Lett. **31**, 811 (2006).
16. N. Schunk and K. Petermann, IEEE J. Quantum Electron. **22**, 642 (1986).